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May 8, 1998

Goddard Space Flight Center
Greenbelt, MD 20771

ATTN: Code 216/ Mr. Michael McGrath, Contracting Officer

SUBJECT: Purchase Order No. S90211-Z

Dear Mr. McGrath,

Please find enclosed the final research report of activities accomplished by Dr. Elizabeth Newton on the NASA contract to Dynetics, Inc., S90211-Z, entitled "An Investigation into the Elementary Temporal Structure of Solar Flare Hard X-Ray Bursts Using BATSE." Delivery of this report constitutes completion of all activities, specified under Reports of Work clause C.2.a, for Purchase Order No. S90211-Z.

If there are any questions regarding this delivery, please contact Dr. Elizabeth Newton or the undersigned at 256/964-4277.

Sincerely,

DYNETICS, INC.

P J Nicaise

Phyllis J. Nicaise
Contracts Manager

Enclosures: (1)

cc: Dr. J. Norris, Technical Representative, Contracting Officer, Code 660.1
Publications and Graphic Services Section, Code 253.1
NASA Center for Aerospace

FINAL RESEARCH REPORT

"An Investigation into the Elementary Temporal Structure of Solar Flare Hard X-Ray Bursts Using BATSE"

NASA Purchase Order No. S-90211-Z
Cycle 7 CGRO Guest Investigator Program

May 1998

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Abstract

The research performed under this contract is part of an on-going investigation to explore the finest time-resolution hard X-ray data available on solar flares. Since 1991, the Burst and Transient Source Experiment (BATSE) aboard the *Compton Gamma Ray Observatory* has provided almost continual monitoring of the Sun in the hard X-ray and gamma-ray region of the spectrum. BATSE provides for the first time a temporal resolution in the data comparable to the timescales on which flare particle energization occurs. Under this contract, we have employed an important but under-utilized BATSE data type, the Time-To-Spill (TTS) data, to address the question of how fine a temporal structure exists in flare hard X-ray emission. By establishing the extent to which "energy release fragments," or characteristic (recurrent) time structures, are building blocks of flare emission, it is possible to place constraints on particle acceleration theories.

We have utilized a spectral estimation technique, known as Lomb's normalized periodogram, to overcome the challenge of computing the power spectra of the unevenly sampled TTS data. By comparing the flare's power spectra to the expected power arising from Poisson noise, we obtain measurements of the smallest, statistically significant timescales present in the data. We have found, in an initial sample of 100 flares, that the smallest statistically significant timescales detected in a single flare are: 89 ms (30 May 1991 11:26:06) in channel 0, 117 ms (17 May 1991 09:03:20) in channel 1, 167 ms (31 May 1991 16:53:12) in channel 2, and 1.55 s (06 June 1991 01:02:08) in channel 3. We have also found some evidence for the existence of preferred timescales, however, the significance of this finding awaits a larger sample of flares.

The Investigation

The high-energy processes of solar flares can occur on small timescales (typically << 1 s), during which time electrons are accelerated up to energies on the order of 100 keV and ions are energized up to several tens of MeV per nucleon. Early analyses asserted that flares possess characteristic timescales varying from 5-15 s (van Beek et al. 1973, 1976) or from 2-10 s (De Jager & DeJonge 1978). More recent work suggests timescales on the order of hundred of milliseconds exist (Kiplinger et al. 1983, 1984, Machado et al. 1993, Aschwanden et al. 1995). Historically, as instrumentations' ability to resolve time structures has improved, finer time structure has been revealed to observers, leaving open the question of whether still smaller structure exists. For this reason, we have chosen BATSE's high time resolution data to conduct our research into elementary time structures. The existence of a recurrent timescale in flare hard X-ray emission will bolster arguments for a universal acceleration mechanism, operative in both impulsive and gradual flares (Cliver 1996).

Of BATSE's three high time resolution data types (Medium Energy Resolution (MER) data, and the little-used Time-Tag-Event (TTE) and Time-To-Spill (TTS) data), we have chosen to work with TTS data. TTS data mark the amount of time required for a specified number of photons (16, 64, or 256 photons, also called the scaling factor) to be recorded from triggered detectors. TTS data are measured against a 1 microsecond (μs) clock, theoretically the finest time resolution available. However the time resolution obtained in practice (usually on the order of 10 ms) depends on the count rate of the observed flare, as well as the background count rate and scaling factor. TTS observations generally cover hundreds of seconds during a flare event. TTS data are recorded in four independent energy channels: 25-50 keV, 50-100 keV, 100-300 keV, and >300 keV. Each channel's time-tagging is independent of the other channels' count rates, i.e., their memories fill at different rates. Typically, because count rates are lower in the higher energy channels, more of the event's duration is recorded in the higher energy channels. Figure 1 displays TTS data in four channels from a GOES C-class flare observed on 8 June 1991 at 04:12:25. (A 5 bin accumulation was applied for plotting purposes only.)

As for the remaining two high time resolution data types, TTE data record individual photon arrival times with a resolution as small as 2 μs in a ring memory buffer. Typical TTE data provide only a few seconds of observations, so we have chosen to focus instead on the longer TTS data sets for which it would be more likely to generate statistically significant results. TTS data also provide a longer dataset than MER data, which consist of approximately 32 seconds of 16 ms observations, followed by additional observations with 64 ms time resolution.

Previous investigations into fine time structure have relied predominantly on time-domain signal analysis. Van Beek et al., Kiplinger et al., Machado et al., and Aschwanden et al., all have utilized peak detection or pulse-fitting algorithms on time series data.

However, there are substantial drawbacks to such approaches. For example, a quantitative likelihood cannot be placed on the 20 ms transients identified by Kiplinger, so one cannot be certain that they did not arise by chance in Poisson noise. Aschwanden et al.'s methods cannot resolve timescales less than 0.3 s. And such time domain techniques cannot address the issue of recurrence or characteristic timescales.

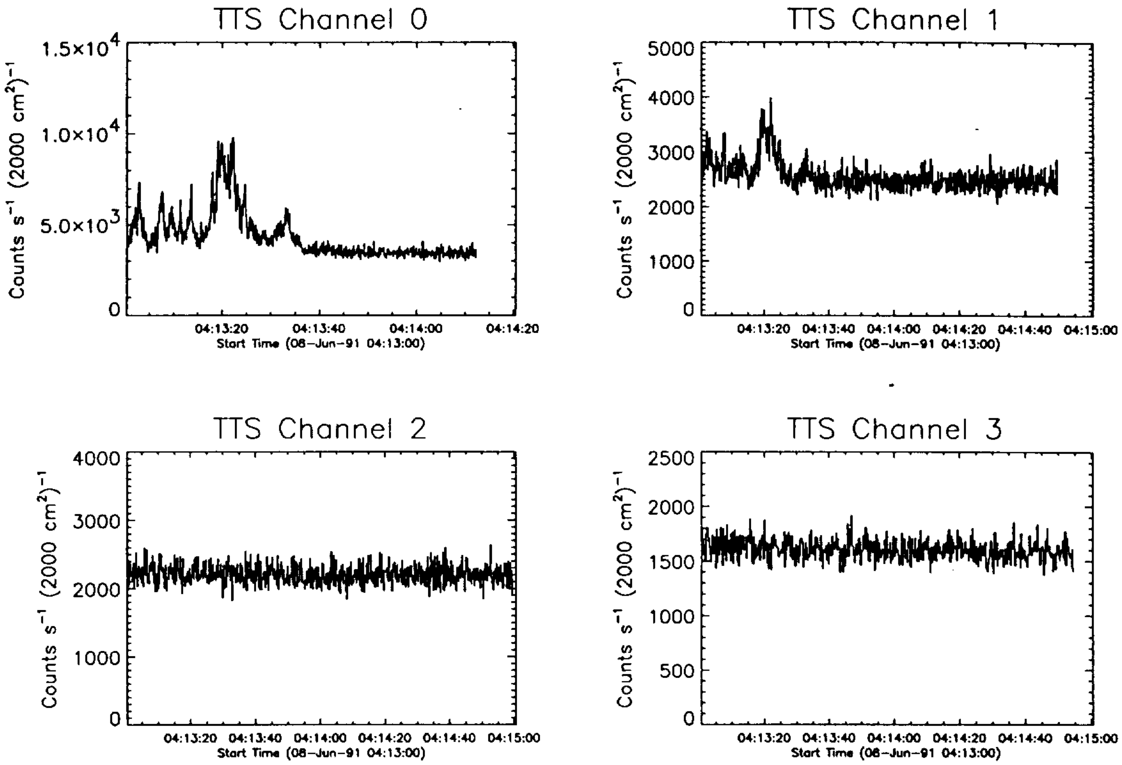


Figure 1. Four-channel TTS Data Taken During a GOES C-Class Flare Occurring 08 June 1991 at 04:13:00

We have taken a different tack in this investigation. Frequency domain techniques are better suited to searching for recurrent time variations than time series analysis, particularly in distinguishing a real, rapidly varying signal from the temporal fluctuations expected from Poisson noise. The essence of this investigation is to determine a timescale in the time series data which occurs more often (with a given significance level) than would be expected from random realizations of the Poisson noise. In order to make this distinction, analysis must be performed in the frequency domain, i.e., with the power spectrum of the time series data. Hoyng (1976) details an expression for the expected high frequency power arising from a Poisson noisy signal (elaborated from Middleton 1960) and provides a means by which to compute the uncertainty in the observed signal's power spectrum due to noise present in the data. Utilizing these tools, it is possible to determine the point at which the observed data begins to show statistically significant evidence of recurrent timescales (that is, when its power spectrum deviates from the expected high frequency power arising from Poisson noise). Brown, Loran, & MacKinnnon (1985) applied this method to the *Solar Maximum Mission*'s Hard X-Ray Burst Spectrometer (HXRBS) data in order to establish that the minimum statistically

defensible timescale could be no less than 100 ms, for an instrument with HXRBS's sensitivity. We have implemented this approach to determine BATSE's instrumental limitations on timescale detection as well.

Fourier analysis is normally applied to time series data in order to compute power spectra, but TTS data present a particular challenge in that they are an unevenly sampled signal. By necessity we implement Lomb's method of power spectrum estimation (Lomb 1978, Press & Rybicki 1989) which is capable of handling unevenly spaced data. This method is preferred to employing interpolation between the unevenly sampled data, as interpolation has been demonstrated to have potentially disastrous results (Scargle 1982). Scargle (1982) has shown that Lomb's normalized periodogram has the simple statistical behavior and time translation invariance of a discrete fourier transform of evenly spaced data and is equivalent to least-squares fitting of sine waves to the data. Lomb's method also permits the straightforward computation of a false alarm probability, that is, the probability that a peak in the spectrum arises from noise fluctuations rather than actual signal variability. Examples of the power spectra, computed using Lomb's method, are shown in Figure 2 for the flare depicted in Figure 1. In addition to the dash-dot line indicating the expected high frequency power arising from Poisson noise, the dotted and solid lines show the power levels at which the spectrum exceeds the 50% and 99.9% significance levels, respectively. The power spectrum exhibits the general shape expected for noise-contaminated data, consisting of a frequency-dependent component and a frequency-independent (white) component arising from noise (Hoyng 1976). In channels 0 and 1 there are significant timescales indicated by the power spectra's peaks. However, the spectra of channels 2 and 3 reflect the predominantly noisy background observed (reference Figure 1).

A sample of 100 flares, observed between May and July 1991, was initially chosen for analysis from the more than 747 triggered flares observed by BATSE since launch. The smallest time resolution obtained in practice in the TTS data for these flares was 213 μs, 183 μs, 235 μs, and 578 μs for the four energy channels respectively, with the average sampling interval being 10 ms, 19 ms, 30 ms, and 60 ms.

For this sample of flares, we then computed the smallest, statistically significant timescales actually detected (indicated by peaks in the power spectra exceeding the 0.001 false alarm probability level). The timescales were 89 ms in channel 0 for the 30 May 1991 11:26:06 flare, 117 ms in channel 1 for the 17 May 1991 09:03:20 flare, 167 ms in channel 2 for the 31 May 1991 16:53:12 flare, and 1.55 s in channel 3 for the 6 June 1991 01:02:08 flare.

In order to determine whether there are preferred timescales in this flare sample, we constructed the sample's number distribution, plotting the number of flares exhibiting a specified timescale against timescale bins. Timescales were binned into 100 ms bins prior to counting the number of flares exhibiting a given timescale. Figure 3 displays these number distributions for channels 0 and 1. We find that a number of timescales exist, around which groupings occur. For channel 0, there is an apparent grouping of

flares which have timescales between 300-500 ms. In channel 1, the grouping is in the 500-600 ms range. (The plots only depict timescales under 5 s).

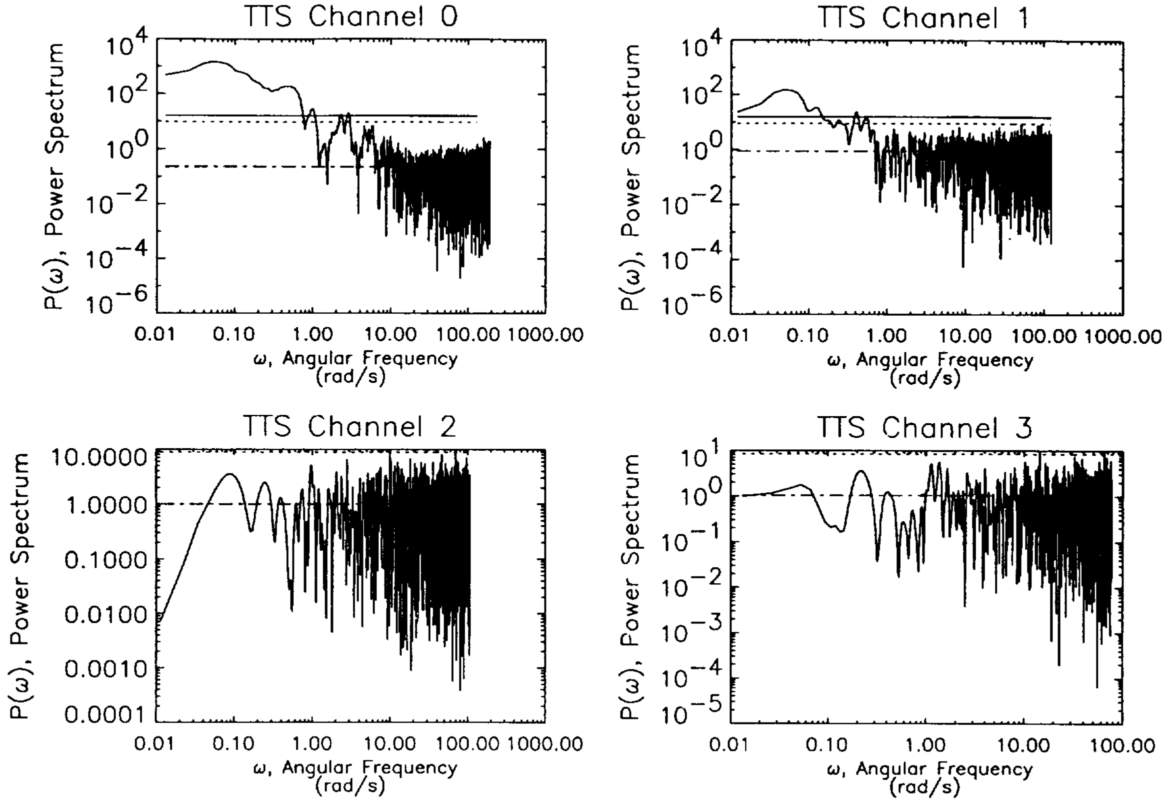
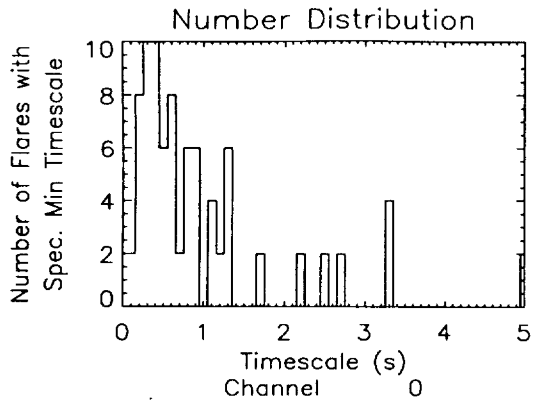
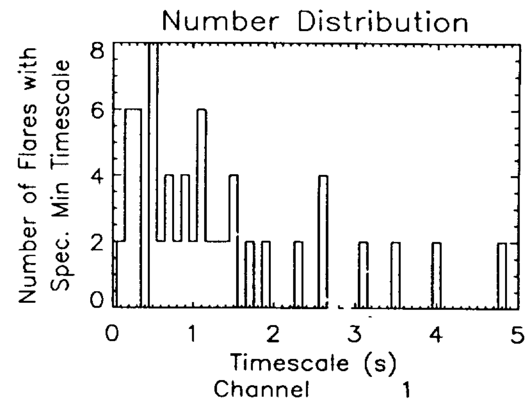


Figure 2. Power spectra computed from the time series data depicted in Figure 1 for the 8 June 1991 04:13:00 Flare. The solid line marks the level at which power exceeds a false alarm probability of 0.001 (99.9% certainty). The dotted line depicts the 0.5 false alarm probability level (50% certainty). The dash-dot line is the average Poisson noise power in the data. Note that the power spectra of channels 2 and 3 never attain any significant power level, i.e., the data are predominantly noise.

These results are quite exciting since they reveal the behavior of hard X-ray emission with the finest time resolution ever available. This rich data set will be the focus of further analysis, particularly for developing a number distribution. Investigations into the relationships between timescales in the different energy channels, as well as the correlation between flare intensity and timescales are underway. A manuscript entitled, " Timescales Evident in BATSE-Observed Solar Flare Hard X-Rays" is under preparation for submission to *The Astrophysical Journal.* The manuscript will cover a larger sample of triggered flares than discussed here and will detail the results' implications for particle acceleration theories.

Figure 3. The number of flares in the sample with a specified timescale in channels 0 and 1.





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